multiple of the resonant frequency, for example, to provide increased field member movement for a reduced amount of energy.

[0033] The circuitry **51** includes an intermediate waveform generator **52** that generates a bipolar square wave **61**. The bipolar square wave **61** has the PWM waveform characteristics described above. The circuitry **51** also includes a low pass filter **53** coupled to the intermediate waveform generator **52**. The low pass filter **53** may be desirable to reduce the relatively sharp edges of the bipolar square wave **61**. The low pass filter **53** may be a double-sided low pass filter, for example, 500 Hz-1 kHz.

[0034] The low pass filtered bipolar square wave is illustrated by the line **62** and may be referred to as the drive PWM waveform. Illustratively, the circuitry **51** generates the drive PWM waveform **62** to have a decreasing amplitude for a number of pulses and a constant amplitude after the number of pulses. The number of pulses may be any number of pulses and may be based upon desired operating characteristics, for example, duration and/or type of the haptic feedback, and/or mechanical characteristics of the haptic actuator. As will be appreciated by those skilled in the art, the amplitude may be constant after the number of pulses as the haptic actuator, or more particularly, the field member **50** may be at a steady state. Thus, just enough energy or amplitude may be used to maintain the steady state operation.

[0035] The threshold or number of pulses that are decreasing in amplitude before generating constant amplitude pulses may be determined based upon an exponential function, for example to reduce the chances of or to avoid an overshoot and hitting the mechanical limit stops **45***a*, **45***b*. For example, if the drive PWM waveform **62** is to be above the threshold, the circuitry **51** may use the threshold limit or constant amplitude of the intermediate waveform **62**. If however, the drive PWM waveform **62** is to be below the threshold, the drive PWM waveform may have a respective amplitude (either decreasing or constant) so long as it is below the threshold.

[0036] To generate the drive PWM waveform **62** from a sinusoidal input, the circuitry **51**, in some embodiments, may apply an algorithm. The algorithm may be embodied using hardware or by software, firmware, etc. loaded into a memory and executed by the circuitry. An exemplary algorithm may be coded as:

```
LPF=tf(1, [½*pi*750)1]);

W=V_Vibe*sign(sin(2pi*f0*T)).*(abs(sin
    (2*pi*f0*T))>(0.95−exp(−2*pi*f0*T/5))); and

WF=(1sim(LPF,W,T)+flip(1sim(LPF, flip(W),T))/2)
```

wherein LPF is the function for determining the parameters of the low pass filter. The "750" is the LPF frequency in this example. The term "(0.95−exp(−2*pi*f0*T/5))" determines how fast the circuitry **51** will generate the decreasing pulse widths to the steady state, i.e. the number of pulses and/or steady state threshold. The threshold is set by the exponential term, "0.95−exp." f0 is the frequency of operation and T is time. Those skilled in the art will recognize that other terms in the algorithm are names given to programming functions.

[0037] The drive PWM waveform **62** may be considered, relative to a typical sinusoidal input, a short duty high voltage PWM waveform smoothed by the low pass filter. As a result of the drive PWM waveform, the electromotive force is, as opposed to the typical sinusoidal input and which is based upon, and more particularly, proportional to the current, may be much larger than the friction force. Thus, the field member **50** may not "get stuck" or the static friction forces may be manageable such that the field member does not crash or bang into the mechanical limit stops **45***a*, **45***b*. Additionally, considering the relatively short duty cycle of the drive PWM waveform, the amplitude that causes the movement of the field member **50** or the vibration may be significantly reduced to a manageable and desired level.

[0038] Referring now additionally to the graph **70** in FIG. **5** a purely sinusoidal waveform is illustrated by the line **71** showing momentum versus an amount of applied voltage. The drive PWM waveform generated by the circuitry **51** is illustrated by the line **72**. Illustratively, the purely sinusoidal waveform **71** may be particularly undesirable as it may cause "crashing" as a result of the spike in momentum.

[0039] While both a controller **22** circuitry **51** of the haptic actuator **40** have respectively been described herein with respect to their functionality, it will be appreciated by those skilled in the art that the circuitry and the controller may be physically embodied on a single physical chip, for example.

[0040] A method aspect is directed to a method of operating a haptic actuator **40** that includes a housing **41**, at least one coil **44** carried by the housing, a field member **50** movable within the housing responsive to the at least one coil, and at least one mechanical limit stop **45***a*, **45***b* between the housing and the field member. The method includes using circuitry **51** to generate a pulse width modulated (PWM) waveform for the at least one coil to **44** move the field member **50** from an initial at-rest position and without contacting the at least one mechanical limit stop **45***a*, **45***b*.

[0041] Referring now to FIG. **6**, in another embodiment, the haptic actuator **40'** may include a permanent magnet **47'** carried by the housing **41'**, and the field member **50'** may include one or more coils that cooperate with the permanent magnet. In other words, in contrast to the embodiment described above, the permanent magnet is stationary (i.e., carried by the housing **41'**) and the coils, as part of the field member **50'** are moving (i.e., connected to the mass). Of course, there may be any number of coils and/or permanent magnets.

[0042] Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.

That which is claimed is:

1. A haptic actuator comprising:

a housing;

at least one coil carried by the housing;

a field member movable within the housing responsive to the at least one coil;

at least one mechanical limit stop between the housing and the field member; and

circuitry capable of generating a pulse width modulated (PWM) waveform for the at least one coil to move the field member from an initial at-rest position and without contacting the at least one mechanical limit stop.